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DESIGN OF UNMANNED FLIGHT VEHICLE SYSTEMS FOR AERODYNAMIC DATA ACQUISITION

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A series of design studies was conducted in order to develop flight vehicle concepts for remotely piloted vehicles intended for aerodynamic data acquisition with particular emphasis on the low Reynolds number flight regime. Five different concepts were developed as part of the senior level Aerospace Systems Design course at the University of Notre Dame. The systems were designed to provide surface pressure and component force measurements on specially instrumented lifting-surface test specimens which were to be carried aloft by a base flight vehicle. The project included the fabrication of subscale, remotely piloted technology demonstrators to validate the base vehicle flight worthiness.

INTRODUCTION

The wind tunnel has traditionally been the primary source of basic aerodynamic data such as surface pressure measurements or component force and moment measurements. It is also used extensively for flight vehicle development. There are many obvious reasons for using the wind tunnel and it has evolved into the most useful of all aeronautical research tools. Unfortunately there are certain situations in which wind tunnel testing is limited. Matching the critical scaling parameters, Mach number and Reynolds number, is not always possible. Of particular concern in the commercial aircraft community is the lack of adequate high Reynolds number testing facilities for the next generation of commercial transports. Presently, there are no wind tunnel facilities available for the level of production testing needed to develop these new aircraft. One option is to explore alternate testing methods to complement the present wind tunnel facilities.

During the past few decades there has been been steady development of a special class of flight vehicle systems referred to as Unmanned Air Vehicles (UAVs) or Remotely Piloted Vehicles (RPVs). Though much of this development has focused on the military applications of these flight vehicles(1), the potential for nonmilitary and commercial application has been shown(2,3). The NASA/Air Force HiMAT program was one of the first major programs in which a remotely piloted vehicle was used to validate a number of advanced vehicle technologies(4,5). As developments in remotely piloted or autonomous vehicle technologies continue, there will be other opportunities for similar applications. These could include validation of numerical methods(6), application to hypersonic flight testing(7), or possibly the use of subscale vehicles at relatively low altitudes with which both Mach and Reynolds number for the next generation transports could be matched(8).

The application of RPVs to the acquisition of aerodynamic data on components or complete configurations was the focus of this study. A number of successful applications of similar efforts have been documented(9,10). Because this study was conducted as part of a senior level, undergraduate engineering design course, its scope was limited by the expertise of the student members of the design teams. For this reason it was decided that the integration of instrumentation and flight vehicle and system control were the most critical basic issues and could be addressed with an application in a "less hostile" flight regime. Therefore the low Reynolds number testing problem was considered. This appeared to be well suited to the RPV application and also provided a realistic design challenge.

REQUEST FOR PROPOSALS

The project was defined using three different requests for proposals (RFPs). These identified concepts which could be used to collect surface pressure data, as given below in the Blue Mission, or to collect component force and moment data in the Gold Mission, or a special application for a high aspect ratio delta wing in the Green Mission. The Blue Mission specification is included (see next section) to provide basic mission specifications although the design groups were allowed to take exception with different aspects of the mission definition if justification could be provided.

The mission outlined in the RFP was very general and may have provided an almost unrealistic challenge to the design teams, considering the single-semester timeframe for the project. Unlike some undergraduate aircraft design studies, this project required consideration of the entire system including instrumentation, data telemetry, and system operation and control. These areas are not traditionally considered in an undergraduate curriculum and required independent study on the part of the students. One other aspect of the project was the requirement that the technologies included in the systems be such that the final designs could actually be fabricated in a university laboratory environment for "reasonable" costs. Though the design groups were developing preliminary concepts rather than final designs, if promising designs did evolve, some consideration would be given to performing detailed design studies and actual system fabrication.

The basic organization of the course and the requirements imposed on the students have been described in detail(11). One of the aspects of this course is the requirement that the design teams actually fabricate a technology demonstrator for their aircraft concept. This technology demonstrator is to be used to validate the basic flightworthiness of the configuration and is not intended to perform the actual design mission. These aircraft which are remotely piloted and fabricated using conventional "modeling" techniques are developed during the last three weeks of the course. This requirement introduces the students to a wide range of additional problems and often influences decisions in the conceptual design phase.

The fabrication of prototypes has proven to be a very positive aspect of the course though it requires significant additional effort. Although the time constraints often limit the success of all of the technology demonstrators, the experience of transforming ideas to "hardware" is very beneficial. This approach has been successfully applied in other undergraduate design programs(12) and the RPV applications are well suited to this type of project.

BLUE MISSION RFP

Opportunity

The wind tunnel has served as the primary source of aerodynamic data for flight vehicle configurations. The wind tunnel is used to test subscale models of flight vehicles or to collect basic aerodynamic data. Within the wind tunnel, certain flow conditions such as model position and flow speed can be accurately controlled, but other influences such as wall interference and free stream turbulence are more difficult, if not impossible, to control. Wind tunnel testing can also be limited by the ability to achieve dynamic similarity between the test and actual flight conditions. Remotely piloted vehicles have been used for testing technology demonstrators, but their use in collecting in-flight aerodynamic data has not yet been fully exploited. The use of an RPV for the collection of aerodynamic data at low Reynolds numbers will be the goal of this design effort.

Objectives

1. Develop a proposal for an aircraft and associated flight control and data acquisition system with the following characteristics:

a. Usable as an airborne aerodynamic data acquisition system for collecting surface pressure distributions and other appropriate near field flow information on "two-dimensional" or "three-dimensional" lifting surfaces. The lifting surfaces must be able to be tested at angles of attack from $-20°$ to $+40°$ over a Reynolds number range (based on chord) of 4×10^4 to 1×10^6.

b. Lifting surfaces ranging in size from chords of 4 in to chords of 16 in.

c. Three-dimensional wing configurations with wing spans from 1 to 5 ft should be considered and wing sweep angles from $-20°$ to $+30°$.

d. An instrumentation system capable of collecting all necessary associated data such as airspeed, angle of attack, etc., with sufficient accuracy in order to provide useful aerodynamic information.

2. Take full advantage of the latest technologies associated with lightweight, low cost radio controlled aircraft and propulsion systems. Since this system may be expected to operate in a wide variety of climates and test locations, the safety of the system will be of critical importance. All possible considerations must be taken to avoid damage or injury in case of system malfunction.

3. Develop a flying prototype for the system defined above. The prototype must be electric powered and should be capable of demonstrating the flight worthiness of the basic vehicle and feasibility of the flight control and data collection system. A basic test program for the prototype must be developed and demonstrated with flight tests.

System Requirements and Constraints

The system design shall satisfy the following:

1. All basic operation will be line-of-sight although automatic control or other systems can be considered.

2. Takeoff and landing must be accomplished in a circular area with no greater than a 150-ft radius (50-ft object clearance). Any special landing or takeoff equipment must be considered as part of the system. For repeated flights, system turnaround must be able to be accomplished in 15 min.

3. Only clear weather capabilities need be considered.

4. All airborne instrumentation and associated flight control systems must be included in the design.

5. Two people must be able to accomplish ground handling and system operation.

6. The complete system should be portable in a conventional pickup truck.

7. Noise nuisance must be a consideration both for the operator and the region in which the aircraft operates.

CONCEPT DESCRIPTIONS

This section briefly describes each of the concepts that resulted from the design studies. These descriptions focus on special considerations associated with each design and the manner in which the individual missions would be performed. The concepts are identified by the group names. The Sky Shark and the SPiRiT were designed to satisfy the Blue Mission, surface pressure measurements. The Air Rhino and the MANTA were designed in response to the Gold Mission RFP, component force or moment measurements, while the Delta M was designed for highly swept delta wing applications.

Each of the design groups developed detailed technical proposals which presented information on all aspects of the design concepts. The following is a synopsis from the executive summary that was included in each proposal. This paper is not intended to provide in-depth technical detail on each aircraft but to describe those features considered most important in the development of the concept.

The Sky Shark

The aircraft designed to meet these requirements, the Sky Shark, is shown in Fig. 1. The aircraft's basic specifications are given in Table 1. In the design of this aircraft, accurate data acquisition and aircraft control (in the context of varying test configurations) were decided to be the most important design considerations. To ensure accurate aerodynamic data, the test specimen should be situated on the craft such that it

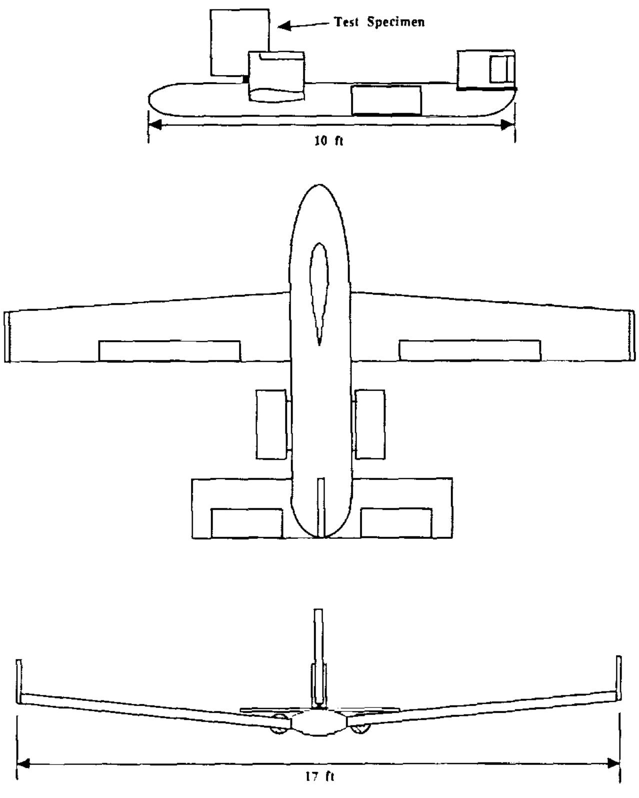

Fig. 1. Sky Shark

experiences the least amount of aerodynamic interference from other parts of the plane. The Sky Shark has the test specimen mounted vertically on top of the fuselage, near the nose. The vertical mounting was chosen to reduce interference from the wing. The section is mounted forward, near the center of gravity, for two reasons. First, near the nose of the craft, proper design of the fuselage can minimize aerodynamic interference with the test specimen. Second, by locating the section near the center of gravity, the forces created by the specimen will not induce large moments.

As Fig. 1 shows, the Sky Shark has a forward, mid-mounted wing with dihedral. From the standpoint of stability, a forward-mounted wing allows the c.g. to be positioned at the front of the aircraft, near the test specimen, as desired. The wing is mid-mounted in order to move it down and away from the test specimen. The dihedral will provide roll and lateral stability which is needed to counteract the destabilizing effects of the test specimen.

Table 1. Basic System Parameters

	Weight (lb)	Span (ft)	Length (ft)	Wing Area (ft2)	Aspect Ratio
Air Rhino	35	9.7	6.7	15	6.3
MANTA	30	15.2	6.7	23	10
Sky Shark	60	17.5	10	34	9
SPiRiT	30	17	10.8	29	13
Delta M	25	14	5.2	14	14

The design includes conventional horizontal stabilizers with oversized elevators for longitudinal stability and control. For lateral stability and control, a single vertical tail with oversized rudders will be used. The control surfaces are oversized in order to correct for any moments created by the test specimen. Roll control will be provided by ailerons on the wings. In order to balance the side forces created by the test specimen, winglets have been positioned on the the wing tips. These active and all-movable winglets are considered rather unconventional and are the result of the requirement to carry an additional lifting surface which will experience high angles of attack. The winglets will be used to balance the side force without creating large yaw moments that would result if the vertical stabilizer were used.

The aircraft will be powered by two ducted fans, mounted on the fuselage behind the wing. It is hoped that proper positioning and integration of the ducted fans will also allow for reduced interference with the test specimen and thus, more accurate data acquisition.

The Sky Shark is capable of meeting most of the mission requirements. For chord lengths of .8 ft to 1.4 ft, the Sky Shark allows testing for the Reynolds number range, 4×10^4 to 1×10^6. If it is desired to test smaller chords, only Reynolds numbers up to 5×10^5 can be achieved. The required angles of attack and sweep can be attained in flight by the aircraft.

The Sky Shark will start its mission on the ground, where it will be fueled, and a test specimen attached. The aircraft will be launched by means of a catapult system. Once in the air, it will cruise at altitudes of 100-3000 ft, where data acquisition will occur. The Sky Shark will fly a rectangular pattern, 1200 ft long by 500 ft wide. The pressure data will be taken for a specific test specimen during steady level flight along the length of the rectangular pattern and stored on board. The craft will allow 20 minutes of testing, with a maximum mission endurance of 45 minutes. The Sky Shark will land on conventional landing gear, which have been retracted up to this point.

The design of the Sky Shark appears to present no significant technical problems. However, some potential trouble spots should be pointed out. Although the greatest effort has been expended in making this aircraft as stable as possible, destabilizing forces and moments from the test specimen may cause problems. This design proposal has assumed that an automatic control system will be incorporated into the aircraft. Such advanced control systems are essential to the success of the Sky Shark.

SPiRiT

The Surface Pressure Readings and Testing (SPiRiT) aircraft is designed to measure the surface pressure distributions about a two- and three-dimensional lifting surface at Reynolds numbers ranging from 4.0×10^4 to 1.0×10^6. The RPV will be able to accommodate lifting surfaces with spans ranging from 1 to 5 ft and chords ranging from 4 to 16 in. The test specimen

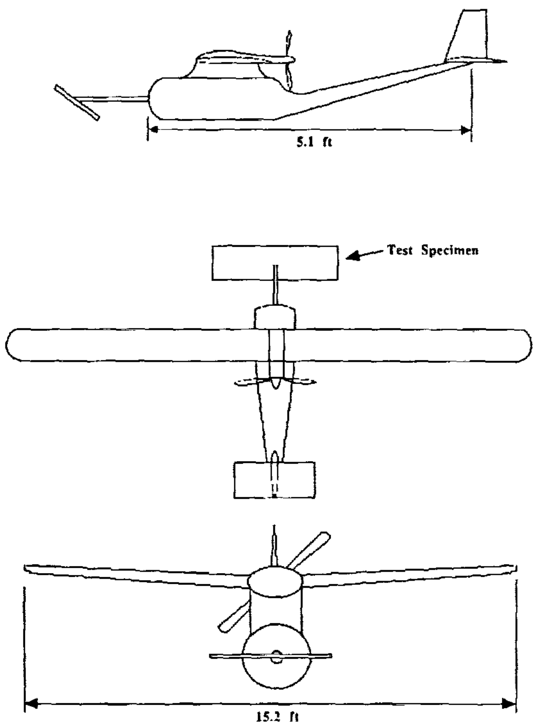

Fig. 2. SPiRiT

itself will be able to rotate in flight to angles of attack ranging from -20° to 40°.

The primary goal of this design is to be able to make accurate measurements of the pressure distribution on the test specimen. Because of anticipated problems with attitude control for extended periods of time, it would be desirable to measure all points of the pressure distribution simultaneously (or as close to simultaneously as possible). Assuming that this can be accomplished, the next important consideration is the influence the RPV has on the flow around the test specimen. To minimize the disturbance, a pusher-propeller, high-wing configuration was selected. Furthermore, the test specimen was mounted as far forward as possible to reduce the interference effects of the wing and propeller. The final configuration is shown in Fig. 2.

The secondary design goals generally involved evaluation of the performance parameters, estimation of stability and control characteristics, and reduction of the weight to improve performance. To maximize the amount of time-on-station data, it is necessary to reduce the drag and weight of the RPV. These goals led to a high aspect ratio wing. The test specimen is mounted forward of the main fuselage and will create large aerodynamic forces which significantly alter the stability and control characteristics. Thus, in order to control these high forces, a large tail and control surface will be required. At the same time, because an automatic flight-control system will be incorporated into the design, it is felt that the RPV should be statically and dynamically stable. This will reduce the workload of the flight-control system.

The actual test specimen itself should be easily interchangeable with other test specimens. This will make the entire RPV a more versatile and easy-to-use experimental tool. For ease of operation, two people at most should be needed for operation. One person controls the data acquisition and the other person controls the flight systems.

The current design has met all these goals. The A/D system collects one complete pressure distribution in 0.2 seconds and stores the data on board for later processing. The RPV will fly for a maximum of thirty minutes and collect data for twenty minutes. It can be operated by two people from a 45.7-meter-(150-foot) radius area.

The design itself, however, is incomplete in several key areas. Preliminary analysis indicated that for the high α conditions and the largest possible test specimen, the main wing would be required to carry a significant download. Thus, basic trim and trim drag considerations must be considered in greater detail. One possible design concept to correct this is to have the wing rotate on its pylon so as to produce a downward force without significant rotation of the fuselage. This wing rotation will be coordinated with the test specimen angle of attack and flight velocity to ensure steady level flight of the aircraft. This will be accomplished by the automatic flight control system. Perhaps a simpler solution would be to invert the specimen for positive angle of attack testing, although such a strategy means that positive and negative angle of attack tests must be completed in separate missions.

There are other considerations that must be addressed in order to evaluate this concept. The proposed data-acquisition system uses four parallel-processing A/D converters to increase the sample rate. This type of parallel processing is complicated and very expensive, and details for such a system have not been addressed. Similarly, the Automatic Flight Control System utilizes a closed-loop feedback system to regulate the airspeed and angle of attack of the test specimen. To save space and weight, the RPV was not equipped with this processing capability. The pertinent information must be radioed to the ground and the correction signals radioed back to the RPV. It is possible that the telemetry system will take too long to encode, transmit, and decode the data. If the telemetry system does take too long, the controls will not respond to the changing environment as desired and the acquired data will be useless.

It is generally recognized that the design of this RPV is still in its preliminary stages. Another iteration of the design process should bring the final design of this concept into a much sharper perspective.

MANTA

This remotely piloted vehicle was designed to collect aerodynamic data on airfoil test specimens at low Reynolds numbers. The aircraft test section is located forward of the aircraft to reduce aerodynamic interference between the flight vehicle and the test section. Its name is the result of its "manta ray" appearance. The aircraft has a 19.4-ft wingspan, an aspect ratio of 13 and a fuselage length of 11.8 ft. The aircraft is fitted with twin 3-hp engines mounted on either wing. Data will be

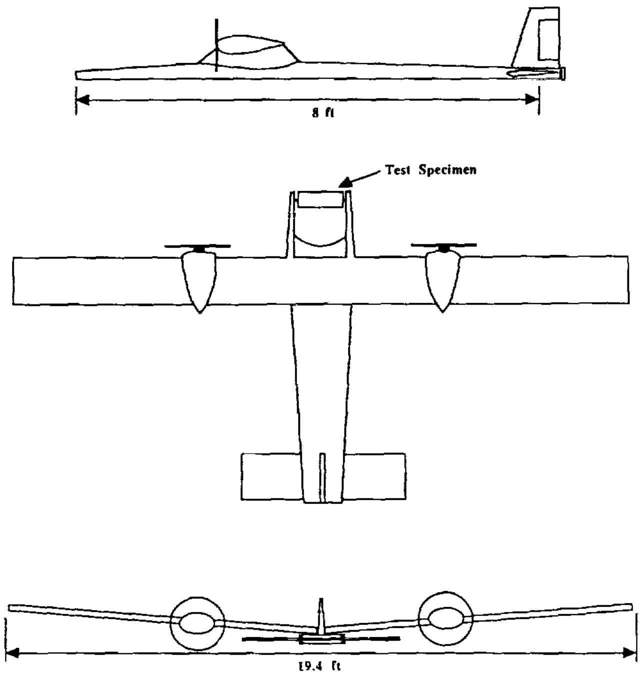

Fig. 3. MANTA

taken using a force-balance system and then radioed to a ground receiver. The MANTA incorporates an automated control system which will control the craft during the data acquisition phase of the flight.

The goal of the MANTA vehicle is to collect actual flight load data for primarily two-dimensional airfoil sections. The variation in test-section angle will be from -20° to 40° with the Reynolds number varying in a range from 4×10^4 to 1×10^6.

The MANTA aircraft is designed for flight under clear weather conditions only. It is operated under line-of-sight conditions due to the nature of the remote control system and the two man limitation of the ground operations team. The amount of wind in which the MANTA can safely operate and the effect of wind gusts on the aircraft still need to be determined. The MANTA is designed to take off using a conventional landing-gear arrangement. Two wheels are located on either side of the fuselage beneath the wing, and the third wheel is a steerable tail wheel located just beneath the vertical stabilizer.

A study of the priorities yielded the following design goals: (1) Wide range of test conditions; (2) Accurate data collection; (3) Good durability; (4) Efficient cruise performance; (5) Cost; (6) Ease of use; and (7) Ease in manufacturing. Based on these, many designs were proposed and evaluated. The resulting concept places the test section forward of the aircraft fuselage and wing. The test section is supported by two booms which are located on either side of the fuselage with a constant separation distance of 2 ft. This allows a maximum test section span of 2 ft. Twin 3-hp engines are mounted on either wing 4 ft from the fuselage centerline. The empennage is located 7 ft from the aircraft center of gravity. The vertical tail has been sized to provide directional stability and to allow a safe landing under one-engine-out conditions. The horizontal tail is sized to ensure longitudinal stability throughout the Reynolds number range and the test specimen angle-of-attack range. The final specifications of the MANTA vehicle can be seen in Table 1 and a schematic of the design is given in Fig. 3.

One of the most difficult tasks involved the proper sizing and movement of the horizontal stabilizer. Large amounts of lift will be generated by the test section at the high angles of attack. At present the horizontal tail is sized so as to allow full test section angle-of-attack range. However, this will sometimes dictate that the aircraft itself must actually fly at a negative angle of attack to achieve steady level flight. Data collection while the aircraft is in a steady maneuver should be investigated to determine feasibility and possible benefits over straight-and-level flight data collection.

Another potential problem that was identified and was not resolved was the difficulty in determining the lift effects of the fuselage. In order to support the booms, the proposed fuselage is very wide and rather thin. Its contributions to the total vehicle aerodynamics could not be determined with the analytical tools at hand. The actual effect must be studied in order to ensure that desirable stability and handling characteristics are obtained during flight.

Air Rhino

The Air Rhino is a remotely piloted "airfoil test platform" airplane. It is designed to measure the component forces on easily interchangeable test airfoils for low Reynolds numbers and varying angles of attack. A three-view drawing and specifications summary are given in Fig. 4 and Table 1.

The data will be gathered in a steady flight environment. The flight plan calls for ascending to cruise altitude and, once there, flying a series of straight, level, unaccelerated test runs where data will be taken. The flight path is controlled by an autopilot system. While the plane is circling back for another test run, the pilot may make adjustments in test airfoil angle of attack or autopilot-programmed flight velocity. Fig. 5 is a schematic of a proposed data sampling mission.

Measurements of the lift, drag and moment on the vertically mounted test airfoil will be made using a specially designed force balance. Other measurements to be taken include the static pressure, the dynamic pressure, the temperature, the plane angle of attack, and the test airfoil angle of attack. These data are sent back to a ground-based receiver, where the data are processed and stored by microcomputers.

The propulsion system consists of a pusher propeller mounted behind the test airfoil and the fuselage to avoid flow interference on the test section. The three-bladed propeller is powered by a reciprocating gas engine capable of producing 8 hp at 8000 rpm. The three-bladed propeller was chosen for efficiency and noise reduction. Endurance, range, rate of climb, and rate of descent are all excellent for the Air Rhino, because its propulsion system is designed for the top velocity of 200 ft/s, so the engine is overpowered for the middle speed ranges.

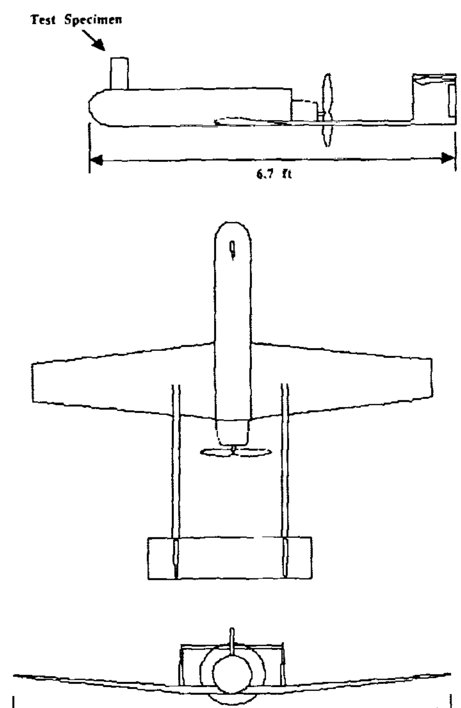

Fig. 4. Air Rhino

Air Rhino wing has a 9.8-ft span, 1.5-ft mean chord wing with spar-and-rib construction. The tail and horizontal stabilizer are located at the end of long twin composite booms mounted aft of the propeller. Three control surfaces are used: ailerons, rudder and a stabilator. These surfaces are actuated by independent servos, as are the flaps, the landing gear and the throttle.

Since this was a preliminary concept study, there are some areas that will require future study. These include development of control to compensate for both the moment and the force of the test airfoil and a more detailed evaluation of the aerodynamic interference between the test specimen and fuselage surface flow and propulsion system.

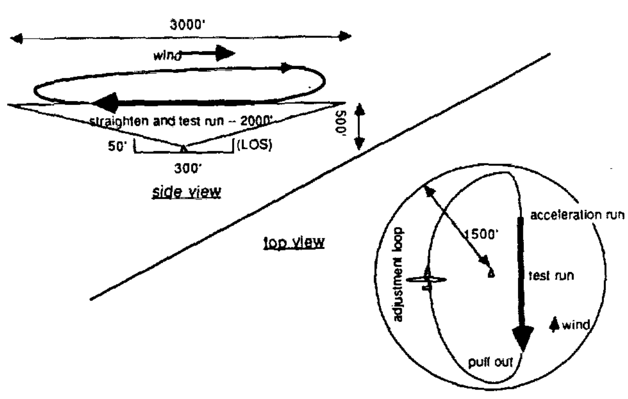

Fig. 5. Typical Data Collection Mission Flight Plan

Delta M

The mission requirements for the performance of aerodynamic tests on a highly swept delta wing planform posed some unique problems. These included aerodynamic interference, structural support, data acquisition and telemetry, aircraft stability and control, and propulsion system integration. However, since the overall integrity of the aircraft is of primary importance, the preliminary concept was selected in order to arrive at a basic design suitable for further development.

The proposed aircraft is a testbed for a class of highly swept, delta wing planform models used in aerodynamic testing. The overall aerodynamic configuration of the proposed aircraft incorporates twin tail booms, a low horizontal tail, twin vertical tails, a fuselage "pod," and a low-mounted, rectangular-planform wing (Fig. 6). With the exception of the twin tail booms, which are the result of concerns over the aerodynamic interference with the wake of the delta wing model, all of the configurational components are relatively conventional.

The data acquisition system incorporated in this design has the advantage of being extremely fast. It is designed for the rapid sampling of up to 100 pressure ports. During each test flight the test engineer will be able to test any of 20 angles of attack in the Reynolds number range of 5.5×10^5 to 1.65×10^6. A typical mission would allow for 28 tests during each flight with an average flight duration of 30 minutes.

This aircraft will be catapult launched in order to reduce fuel requirements and to limit takeoff distance. Once in the air the aircraft will be remotely controlled by the ground-based pilot until the test altitude is reached, at which time control will be transferred to a computer-based, automatic control

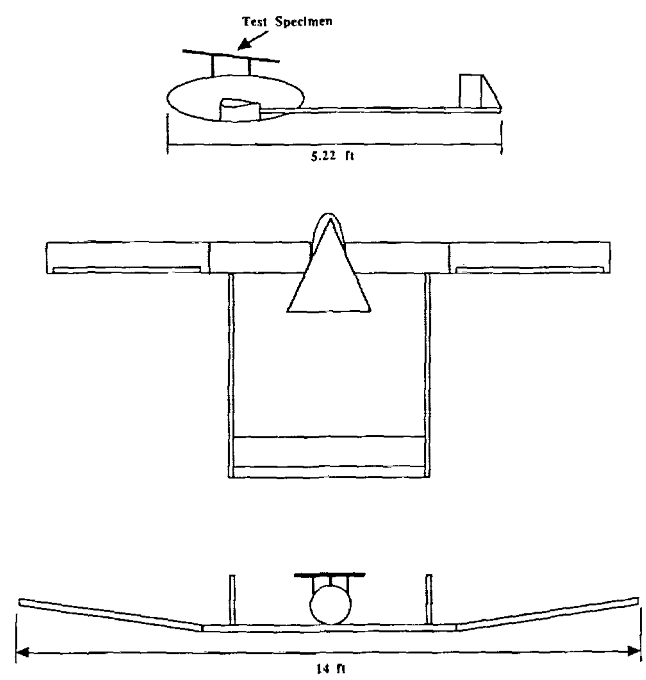

Fig. 6. Delta M

system. This will allow for the standardization of the data acquisition procedure. As a safety feature, the test engineer always reserves the right to override the automatic system and resume manual control. After the flight, the proposed aircraft will land on the deployed spring-loaded landing gear.

The propulsion system proposed for this design uses a ducted fan unit housed in the rear of the fuselage. This system was chosen because of concerns about interference between the propulsion system and the test specimen. By locating the inlets away from the upper surface of the aircraft (wings, forward end of fuselage, rear end of fuselage, etc.), good flow quality should be ensured. Because of the twin tail boom configuration, potentially disrupted flow from the test model will not be allowed to impinge upon the vertical control surfaces. Also, the model will be mounted in a region above the fuselage outside the boundary layer.

Stability and control considerations are very important for a remotely piloted vehicle. Due to the placement and size of the tail surfaces, sufficient static stability is assured. Though maneuver performance is not critical, adequate controllability must be achieved. Due to the placement of the delta wing test specimen above and slightly aft of the aircraft center of gravity, the pitching moment created by the lift and drag on the model will work to cancel each other at the extreme angles of attack.

Although this aircraft was designed as a "work-horse," it has good performance characteristics. The typical flight duration will allow for the collection of significant amounts of data and a wide range of test conditions. Particular concerns which must still be addressed include details on the inlet design and ducted fan integration, landing gear installation, and details of the automatic flight control system.

SYSTEM DESIGN CONSIDERATIONS

The concepts defined above were the result of a series of preliminary design studies. The primary design goals of each concept were defined by the design teams; thus, the emphasis of each team was somewhat different and each encountered different problems. It should be stressed that this project considered the design of a complete system, not simply an airframe. Therefore, the potential success of the entire system rested upon the successful integration of the individual subsystems. The following is a brief summary which addresses each of the primary technical areas and highlights methods used in the design process and problems encountered.

Data Acquisition and Flight Control

The design of the data acquisition system and the integration of the instrumentation into the flight vehicle was the most difficult aspect of the design project[13]. Since only a general description of the test specimen was provided, detailed definition of the instrumentation was difficult. In this low Reynolds number range, component forces are usually relatively low, requiring a rather sensitive balance. On the other hand, the flight testing and ground handling requirements dictate a durable and robust system. A similar dilemma is encountered in conducting surface pressure measurements,

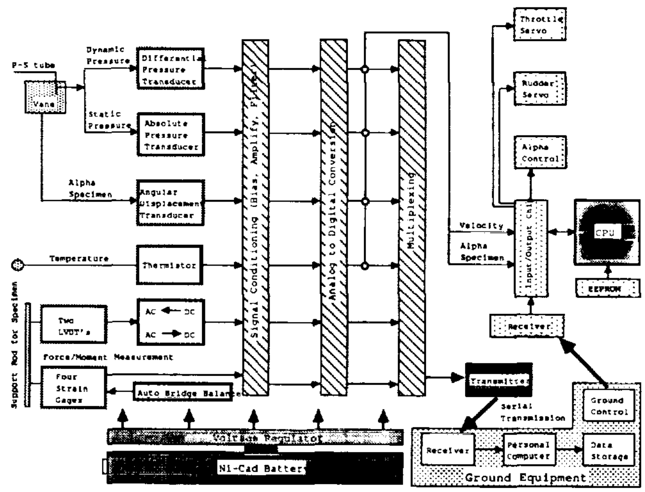

Fig. 7. Schematic of Data Acquisition System

since the low speeds result in rather low pressure differences which establish a need for rather large, heavy transducers.

Defining onboard data processing and storage as well as the data telemetry requirements for these systems was equally complex. Purdue University[14] has been developing an RPV-based flight test program and provided useful input based on their experiences. The accuracy of onboard instrumentation and the design of an automated flight planning system are well beyond the scope of this preliminary concept study, but considerations of each were made by the design teams. Fig. 7 illustrates the proposed system for the Air Rhino, which included the aerodynamic and flight data acquisition systems, data processing, and transmission equipment.

Aerodynamics

The aerodynamic design of the vehicles was rather straightforward. In each case relatively simple, conventional designs proved adequate for the mission. Since neither range nor endurance, typical aircraft design parameters, was considered critical, there did not appear to be an overwhelming need to "optimize" the aircraft aerodynamics.

The overriding concern was the placement of the test specimen so that it would encounter as close to free stream conditions as possible. This resulted in the placement of the test specimen as discussed above. Unfortunately, the tools available to predict the three-dimensional flow fields associated with the base vehicle and the test specimen were quite limited. Simple vortex models were used but more analysis using interfering lifting surface methods would be required. Fig. 8 illustrates the type of results achieved with these simple methods. It shows the induced velocity at the test specimen resulting from lift generated by the main wing for a single flight condition. This type of data was used to determine the wing/test specimen spacing. Table 2 contains a comparison of some of the basic aerodynamic parameters for the five concepts.

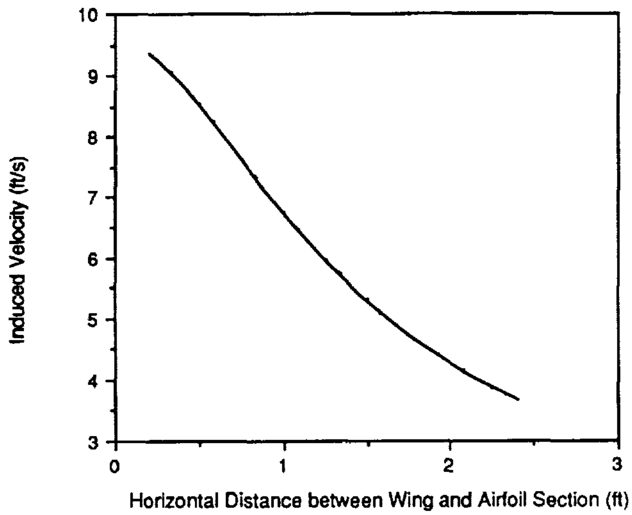

Fig. 8. Induced Velocity at Test Specimen due to Wing Lift

Table 2. Basic Aerodynamic Parameters

	Airfoil (main wing)	C_{D_0} (Aircraft)	Taper (wing)	Dihedral (wing)
Air Rhino	Wortmann FX63-137	.015	0.6	5°
MANTA	NACA 23012	.0115	0.5	—
Sky Shark	NACA 1408	.023	0.8	10°
SPiRiT	Gottigen 797	.027	1.0	3.5°/5.8°
Delta M	NACA 4415	.015	1.0	8°

Airfoil Selection. Since the test specimen is flown in the low Reynolds number regime, the primary lifting surfaces and control surfaces must also operate in this regime. There are numerous problems associated with low Reynolds number airfoil performance such as reduced $C_{l_{max}}$, increased sensitivity to surface roughness and nonlinear or hysteretic behavior of C_l. Since flight performance was not considered to be the most critical aspect of these systems, some of the groups selected rather conventional (NACA) airfoils where others used newer, low Reynolds number airfoils.

An additional problem is the availability of adequate aerodynamic data. There is a limited number of sources[15] that can be used to provide airfoil data, but, considering the rather wide Reynolds number range in which these vehicles operate, reliable data was difficult to find. This was particularly true in drag prediction, since much of the component drag data and traditional drag buildup methods are not well-suited for this low Reynolds number range.

Complex high-lift devices were not used on any of the concepts since most felt that takeoff performance was not critical and the mechanical complexity associated with them would be unwarranted for this mission.

Wing Planform. Rather conventional wing planforms were selected by each group. Each had a rather high aspect ratio, although induced drag was not considered a significant design influence. Wing loading ranged from 1.0 to 2.3 lb/ft^2 which is very low by most flight vehicle standards, but is consistent with large-scale, radio-controlled aircraft operating in this speed range.

The design teams did have access to a simple lifting surface analysis procedure developed by Kroo[16] which proved quite useful in preliminary planform selection. Figure 9 illustrates the results of a trade-off study which investigated the influence of taper and sweep on spanwise c_l distribution. This particular program is an extended lifting line method for which the students have the necessary theoretical background. Therefore, they are better able to interpret the results than if a much more sophisticated method were used.

Fuselage. In each case the fuselage was intended to carry the data acquisition systems, telemetry and control equipment, and fuel. For the Delta M it was also intended to house the ducted fan engine. Since the test specimen was mounted near the fuselage in each case, aerodynamic interference with the fuselage was considered important, but prediction of this interaction was limited by the available tools.

Contribution of the fuselage to the aircraft drag was estimated using component drag buildup methods, but the results were considered approximate at best since the empirical data base from which the component contributions were determined was developed at a larger Reynolds number.

Propulsion

In order to achieve the low cost goals of each of the design groups, off-the-shelf propulsion systems were proposed for each concept. There are a number of two-cycle and four-cycle internal combustion engines which are available for this type of application. Primary design considerations were engine placement, propeller design, and aerodynamic interference of the propulsion system with the test specimen. Table 3 summarizes some aspects of the propulsion systems for each concept.

In an attempt to reduce the interference with the test specimen, two of the concepts proposed ducted fan engines

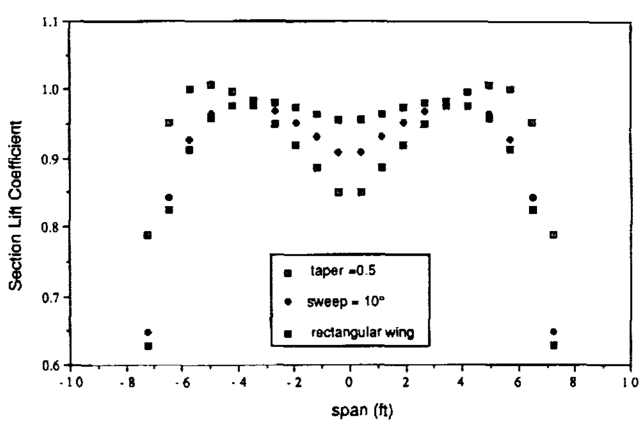

Fig. 9. Dependence of Spanwise Lift Distribution on Wing Planform

Table 3. Propulsions Systems

	Type	Prop	BHP (at rpm)	Weight Fraction (%)
Air Rhino	Internal Combustion (IC)	3-blade pusher	8.0 (8,000)	39.7
MANTA	IC-twin	3-blade tractor	6.0 (7,900)	16.7
Sky Shark	IC	ducted fans	3.0 (16,000)	23.8
SPiRiT	IC	3-blade pusher	7.5 (11,000)	29.4
Delta M	IC	ducted fan	5.0 (19,500)	11.0

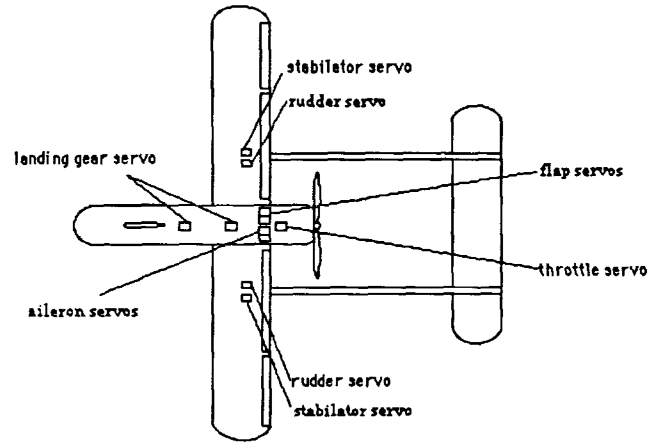

Fig. 10. Control System Actuator Location

which are available in this power range. There is little detailed technical information available on these power plants; therefore, inlet design and the actual influence on the flow field about the body could not be determined at this stage of the design. Two of the other groups selected pusher configurations in order to reduce interference and the third selected a twin-engine design with the engines placed well outboard on the wings. Prediction of the aerodynamic or acoustic interference for these engine placements was not accomplished during this study.

The power requirements and weight fractions for each of the configurations were not critical elements in the design.

Stability and Control

Inherent static and dynamic stability were very important design considerations because of the remote operation of these vehicles. Each group assumed that the vehicle would be piloted by a ground-based pilot during launch and landing phases of a mission and by some form of automatic system during the flight data acquisition phase. A stable platform would also help during the ground pilot phase and aid in consistent test conditions for data acquisition phase. Each group attempted to establish a design which satisfied basic longitudinal static stability with adequate static margins.

Dynamic stability and handling qualities were not addressed in this phase of the design. Handling qualities present a problem with remotely piloted vehicles since accepted standards similar to those for piloted aircraft do not exist. Additional problems related to instrumentation for the ground-based pilot and basic aircraft visibility were also encountered.

Details of the automatic flight control system were beyond the scope of this effort, but other considerations such as required instrumentation, control surface sizing, and certain aspects of the mechanical installation were briefly considered. Figure 10 is a schematic of the actuator locations required for the Air Rhino.

Structures and Materials

Since low cost was one of the primary design drivers for each of these systems, materials selection and structural design were based on existing technologies, many of which are used by the aviation hobbyist. These include wood and fiberglass construction although numerous applications of other composites were included. These materials actually simplify the manufacturing process and maintain reasonable costs.

Preliminary structural analyses were performed for most of the lifting surfaces, which were of semi-monocoque construction. Finite-element analysis using a recently developed design program was conducted in order to establish the validity of a number of the designs and to establish spar locations and allowable deflections[17].

Weight estimation was performed for each of the concepts and this presented some additional problems. Weights data and weight fraction information are not readily available for a large number of aircraft in this class. This limited the reliability of the initial weights data, but since these were rather simple systems, the component weights could be developed. Table 4 illustrated the system weights of the major components for the Air Rhino.

Table 4. Component Weights—Air Rhino

Component	Center of Gravity Locations: Center Gravity location (ft)	Weight (lbs.)
Fuselage hull	1.85	5.0
Booms	4.85	1.4
Horiz. stabilizer	6.25	1.2
Vert. stabilizer	6.35	0.4
Battery	0.583	1.5
Autopilot	1.0	1.0
Test airfoil & force balance	0.167	2.5
Circuit boards & instruments	1.67	0.5
Wing	2.675	5.4
Fuel	3.0	2.0
Engine & Propeller	4.0	8.0
Total accountable weight:		28.9

Table 5. Basic Performance Parameters

	Maximum Range (miles)	Maximum Endurance (min)	R/C Maximum (ft/s)	V Maximum (ft/s)
Air Rhino	100 at 80 ft/s	101 at 55 ft/s	73	200
MANTA	40	30	—	—
Sky Shark	47	40	36	190
SPiRiT	—	30	75	150
Delta M	202 at 100 ft/s	180	33.5	150

Performance

Only preliminary performance estimates were performed for each of the systems. Of primary concern was predicting the time on station as related to the amount of data that could be collected on a single flight. Table 5 summarizes some of the performance characteristics for each of the aircraft. Typical mission times of approximately 30 minutes were established based on onboard data storage limitations and were satisfied by each of the concepts. These would not be considered high performance aircraft. The most limiting performance requirement appeared to be the need for a rather wide, steady, level-flight speed range. This was imposed by the Reynolds number range required for the test specimen. Since the aircraft were not required to perform extensive maneuvers and would operate at low altitude, none of the concepts appeared to be performance limited.

TECHNOLOGY DEMONSTRATOR DEVELOPMENT

Each of the design teams completed a flight-worthy technology demonstrator. The total fabrication time for each was approximately three weeks. The technology demonstrator was required to establish the viability of the basic configuration. It was not required that it include the instrumentation or data acquisitions systems, and it would be controlled by a ground-based pilot.

The design teams were provided with remote-control radio systems and propulsion systems and were responsible for the acquisition of all other materials and complete system fabrication. For reasons of safety and ease of operation, the groups were requested to use a specific electric powered propulsion system for the technology demonstrator. This system produced about 0.2 hp at 6000 rpm and created problems in "scaling" as groups attempted to fabricate the technology demonstrators. They were then forced to build subscale versions of their actual designs which increased problems with low Reynolds number airfoil performance. The electric propulsion systems were also significantly heavier than those proposed for their actual concepts and even though they were not required to carry all of the data collection instrumentation, the weight fractions for the electric propulsion and flight control system exceeded those for the propulsion, control, and instrumentation systems for the actual design. Thus, the technology demonstrators were overweight and underpowered, a situation that should be avoided.

The flight test program consisted of one 2-hour period during the last week of the semester. All of the aircraft launched or took off on their own power and maintained sustained flight for some period of time. The Sky Shark performed a very successful flight and landing and received high marks from the two test pilots. The MANTA provided the most eventful flight when the vertical stabilizer failed due to flutter and separated from the aircraft resulting in loss of control and catastrophic crash. The other three aircraft did fly, although each encountered a pilot control or inadequate power problem on takeoff and therefore "landed" very shortly thereafter. Each incurred damage that could not be repaired within the two-hour period.

Due to the very limiting time constraints placed on the course, the modifications required to continue the flight tests were not performed and the aircraft were retired to the museum. The experience gained by the student designers was not "retired" and demonstrated the challenges associated with successful development of flight vehicle systems.

CONCLUDING REMARKS

The systems described in this paper were conceptual designs resulting from a single-semester undergraduate course. The purpose of the course is to provide the students with design experience at the systems level and to introduce parametric trade-off studies and optimization techniques. This is accomplished by performing design studies on realistic aircraft systems. The mission used for this project involved the design of unmanned flight-vehicle systems for aerodynamic data acquisition. This was a rather complex mission, even though the application involved low-speed subsonic flight.

Five concepts were proposed in order to satisfy this mission. Each was the result of approximately eight weeks of effort. These primary studies indicated that the critical considerations were the data acquisition and instrumentation systems, the flight control systems, and the integration of the test specimen onto the base vehicle. Each of these was addressed by the design teams and a number of solutions were proposed.

The designs illustrated the feasibility of developing a rather low cost flight-test system, but the concepts presented in this paper are preliminary. Additional design studies would be required prior to actual system development.

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